

Advanced BHA Modeling and Drilling & Evaluation Technology to Improve Efficiency in Shale Gas Horizontal Drilling



Shale Gas Typical Drilling Challenges

Challenge /Objective

- Performance Optimization
- Wellbore Placement
- Bit & Motor Durability
- Excessive Sliding
- Extended Reach
- Borehole Quality
- PDC Bit Vibrations
- High Stick-Slip, Torque
- Staying in Zone (Lateral)
- Hole Cleaning, Balling
- Pack Offs, Stuck
- Faulted/NF, Abrasive Format.

Impact

- Reduced ROP, Days on Well
- Production Optimization
- Bit Trips – NPT
- Reduced ROP, Days on Well
- Production Optimization
- Problems Run CSG, Red. ROP
- Reduced ROP, Days on Well
- Reduced ROP, Days on Well
- Production Optimization
- Reduced ROP, Days on Well
- Increased Days on Well
- Reduced ROP, Days on Well

Major Shale Gas Drilling Challenges:

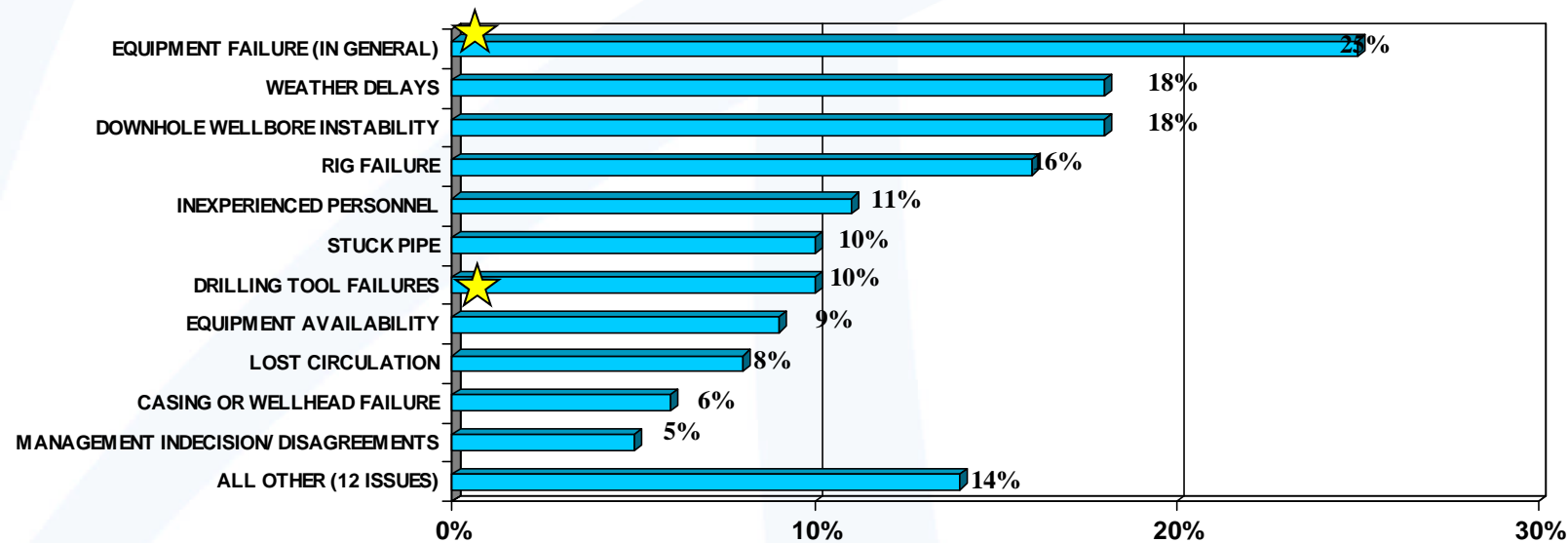
- The formations are difficult – maximize the trip time
- Optimize drilling to increase ROP
- How to steer to the right place in the formation

The Value of Bit and BHA Stability

Drilling system stability has a significant influence on overall reliability (i.e. less vibration = less bit, BHA, and drill string damage)

- Equipment failure is the largest source of non-productive time
- Drilling tool failures specifically cited as a top source for NPT

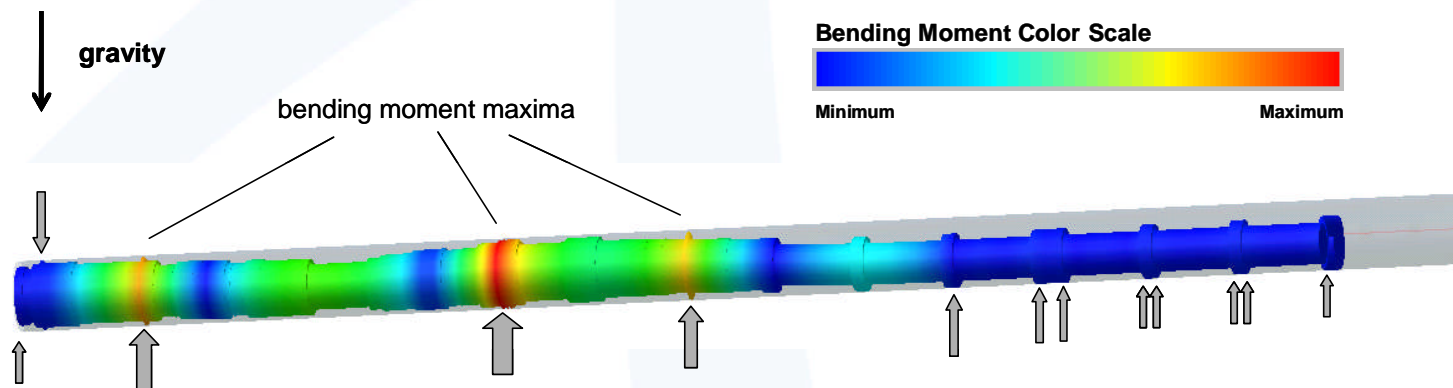
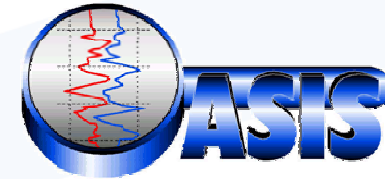
Survey Question: What is your greatest source of NPT?



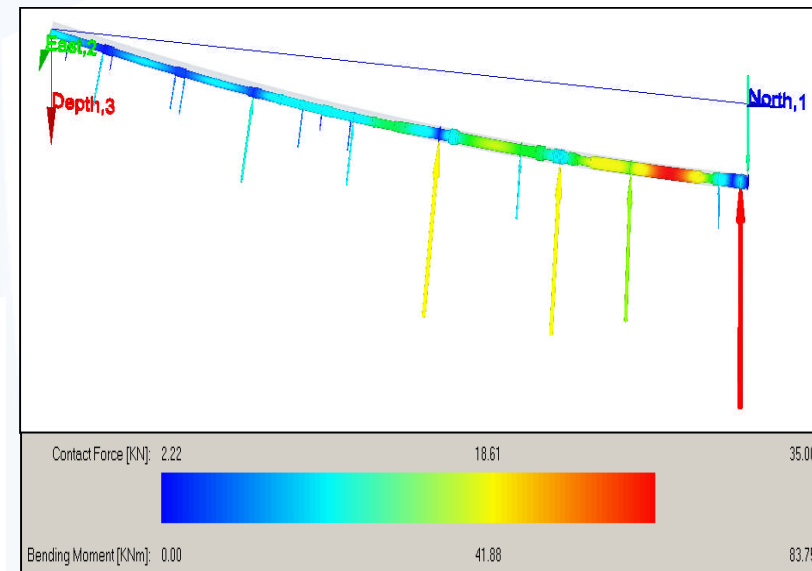
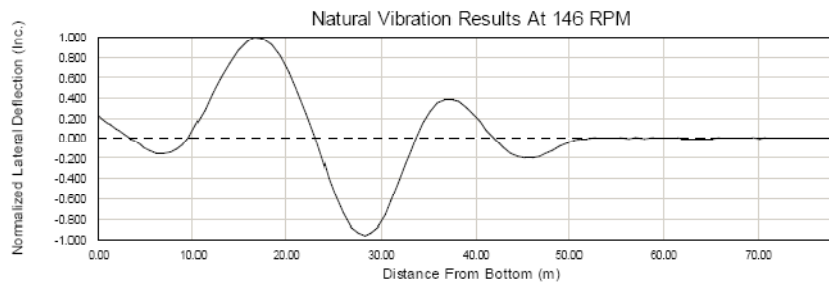
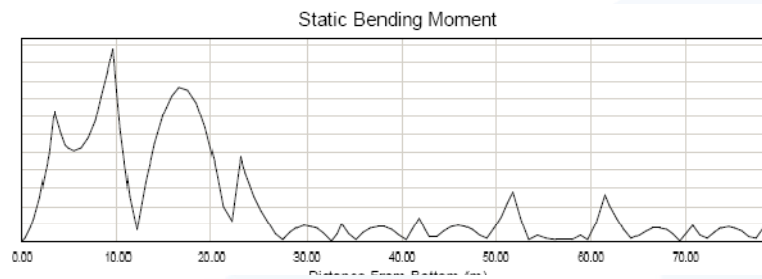
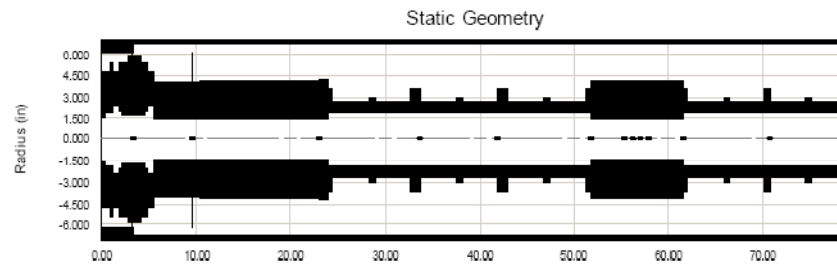
Source: Welling & Company

Drilling Engineering / Optimization

- Internal education and certification program for Drilling Application Engineers
- AKS - Application Knowledge Store
- Advantage Engineering Package
 - Torque & Drag, Hydraulics
- BHASysPro Analysis Software



BHASysPro - Fit for Purpose BHA



Advantage Software for Hydraulic Optimization

| ADVANTAGE Hydraulics Spreadsheet Report Including Cuttings Transport | | | | | | | | | |
|---|---|---------|--------------|--------------------------|-------------------------|---------|---------|--------|--|
| Case - 12_25x13_5_G3_W_COPI_UR_BHAS | | | | | | | | | |
| Operator | Norsk Hydro ASA | | | Facility | Deep Sea Trym | | | | |
| Well | 31/5-3-24 AY1H | | | Field | Troil West Gas Province | | | | |
| General | | | | | | | | | |
| Max Allw.SPP | 300.00 bar | | | Type | Length m | OD in | | | |
| Surface Equipment | Type 4 | | | DP - W56 / 5-135 | 1745.20 | 5 1/2 | | | |
| Bit Depth | 1982.00 m | | | DP - W56 / 5 1/2" FH / | 112.38 | 5 1/2 | | | |
| Bit Nozzles in/32 | 2x11/7x12 | | | Sub - X/O | 1.2 | 7/8 | | | |
| RWD Nozzles | 1" 8 (in/32) | | | Sub - X/O | 12.84 | 8 | | | |
| ROP | 22.00 m/hr RPM | | | 140 RPM | Sub - X/O | 9.30 | | | |
| Drilling Fluid | | | | | | | | | |
| Mud System | Water Based | | | HWDP - 5 1/2" FH / | 27.59 | 5 1/2 | | | |
| Mud Weight | 1.250 sg | | | Sub - X/O | 1.22 | 7/8 | | | |
| Pl V / VP | 14.00 cP / 16.65 Pa | | | Sub - string | 2.32 | 15/16 | | | |
| Gel Strength, 10s/10min | 5.20 / 7.20 Pa | | | Sub - X/O | 0.99 | 5/8 | | | |
| Rheological Model | Herschel-Bulkley | | | HWDP - 6 5/8 FH / HW ... | 9.30 | 5/8 | | | |
| | K: 1.452(Pa.s ⁿ) n: 0.434 [-] YP: 2.660(Pa) | | | Sub - X/O | 0.98 | 7/15/16 | | | |
| Fann 35 Speed | 600 / 300 / 200 / 100 / 6 / 3 | | | Sub - Boat | 0.77 | 7/15/16 | | | |
| Fann 35 Reading | 63 / 49 / 39 / 33 / 13 / 1.1 | | | Bit - under reamer | 5.34 | 13/12 | | | |
| | 63 / 49 / 39 / 33 / 13 / 1.1 | | | NH Sub - string | 2.30 | 8/15/16 | | | |
| Casing / Open Hole | | | | | | | | | |
| Type | OD in | ID in | Bottom MD in | Sub - X/O | 0.98 | 7/15/16 | | | |
| Riser/Booster | | | | HWDP - 6 5/8 FH / HW ... | 27.84 | 8/15/16 | | | |
| Casing | 13 3/8 | | | Sub - X/O | 0.65 | 5/8 | | | |
| Openhole | 13 1/2 | | | NH Sub - stop | 0.80 | 5/8 | | | |
| | 13 1/2 | | | MWD - Nutron/INTEQ | 2.65 | 5/8 | | | |
| Volumes m ³ | | | | | | | | | |
| Annulus Volume | 168.31 Hole Volume | | | MWD - Density/INTEQ | 2.54 | 5/8 | | | |
| String Displacement | 12.17 String Volume | | | NH Sub - X/O | 1.08 | 1/2 | | | |
| | 21.24 | | | Sub - other | 2.73 | 7/15/16 | | | |
| | | | | MWD - BCPM Std 50mm/... | 3.55 | 9/12 | | | |
| | | | | MWD - ONTRAK/INTEQ | 7.01 | 9/12 | | | |
| | | | | MWD - Corus/INTEQ | 2.22 | 9/12 | | | |
| | | | | Flex sub w/ Stab | 3.63 | 7/15/16 | | | |
| | | | | ATK - ASS/INTEQ | 2.52 | 9/12 | | | |
| | | | | Bit - HCN60/INTEQ | 0.37 | 22/14 | | | |
| Flowrate | | | | | | | | | |
| Flowrate | l/min | 4010 | 3710 | 3410 | 3110 | 2810 | 2510 | 2310 | |
| Bit Hydraulics | | | | | | | | | |
| SPP | bar | 185.76 | 164.63 | 145.37 | 128.06 | 111.99 | 98.23 | 100.76 | |
| Surface HP | kW | 2441.5 | 1018.0 | 848.2 | 663.8 | 524.5 | 410.9 | 371.1 | |
| Bit Pressure Drop | bar | 61.52 | 52.58 | 44.32 | 36.76 | 29.91 | 23.77 | 18.34 | |
| %SPP | % | 33.12 | 31.94 | 30.49 | 28.71 | 26.71 | 24.20 | 18.20 | |
| Bypass Ratio | % | 6.3 | 6.4 | 6.5 | 6.7 | 6.8 | 7.0 | 7.2 | |
| Jet Velocity | m/s | 101.2 | 93.6 | 85.9 | 78.2 | 70.6 | 62.9 | 55.3 | |
| Impact Force | lbf/in ² | 15.1021 | 12.9070 | 10.8809 | 9.0242 | 7.3426 | 5.8355 | 4.5019 | |
| HSI | kW/m ² | 5063.93 | 4001.03 | 3096.93 | 2339.07 | 1716.76 | 1216.31 | 824.20 | |
| TFA For Max SPP | in ² | 0.9587 | 0.9587 | 0.9587 | 0.9587 | 0.9587 | 0.9587 | 0.9587 | |
| Bit Pressure Drop | bar | 61.52 | 52.58 | 44.32 | 36.76 | 29.91 | 23.77 | 18.34 | |
| Opt Bypass Ratio | % | 6.3 | 6.4 | 6.5 | 6.7 | 6.8 | 7.0 | 7.2 | |
| TFA RWD optimum | in ² | 0.0491 | 0.0491 | 0.0491 | 0.0491 | 0.0491 | 0.0491 | 0.0491 | |
| HSI RWD | kW/m ² | 2803.80 | 2297.02 | 1867.57 | 1507.74 | 1191.99 | 919.97 | 690.83 | |
| HSI Bit | kW/m ² | 5063.93 | 4001.02 | 3096.93 | 2339.07 | 1716.76 | 1216.31 | 824.20 | |
| System Pressure Loss - W/ Cutting Effect | | | | | | | | | |
| Start Equip | bar | 8.84 | 7.28 | 6.60 | 5.59 | 4.66 | 3.80 | 3.02 | |
| DP, C56, LNR, T80 | bar | 48.39 | 42.90 | 37.66 | 32.67 | 27.94 | 23.48 | 19.31 | |
| HWDP/CSDP | bar | 10.71 | 9.51 | 8.36 | 7.26 | 6.22 | 5.24 | 4.31 | |
| HWDP/AutoTrak | bar | 41.65 | 37.65 | 34.23 | 31.40 | 28.26 | 25.14 | 22.04 | |
| Additional Tools | bar | 6.78 | 6.03 | 5.30 | 4.60 | 3.94 | 3.32 | 2.73 | |
| Annulus | bar | 7.87 | 8.29 | 8.90 | 9.77 | 11.06 | 13.48 | 31.01 | |
| ECD - CSG Shoe | sq | 1.289 | 1.290 | 1.292 | 1.295 | 1.300 | 1.312 | 1.434 | |
| ECD - Bottomhole | sq | 1.301 | 1.303 | 1.307 | 1.313 | 1.321 | 1.332 | 1.450 | |

Operator

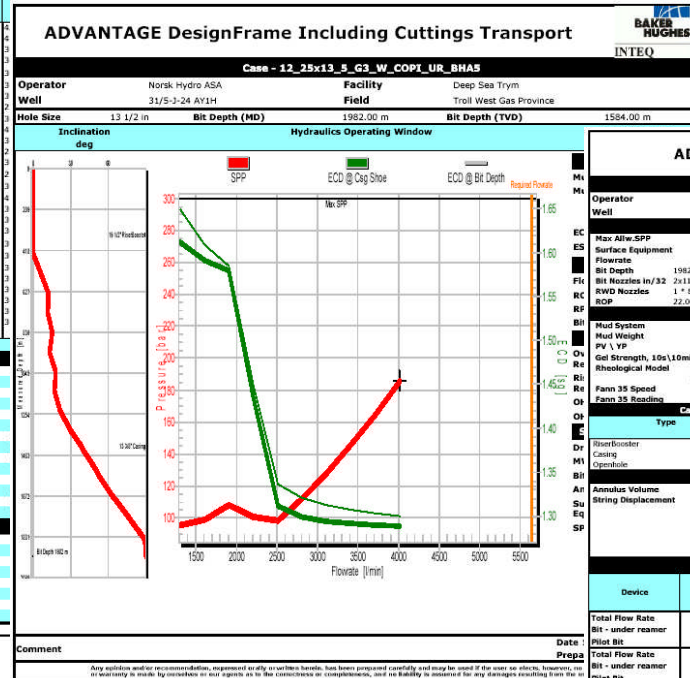
Well

Hole Size

Inclination deg

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100

ADVANTA



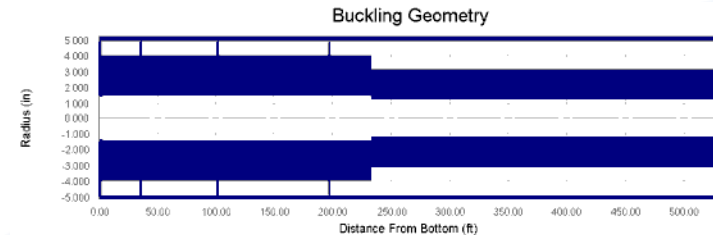
| ADVANTAGE Flow Split Optimization | | | | | | | | | | | | | Baker Hughes | | | | | | | |
|-------------------------------------|--|--|---|--|--------|--|--------------------------|--|---------------------|-------------------------|-----------------|-------------------|--------------|--------|-------------------|---------------|------------------------------|-----------|----------|--|
| Case - 12_25x13_5_G3_W_COPI_UR_BHAS | | | | | | | | | | | | | | | INTEQ | | | | | |
| Operator | | | Norsk Hydro ASA | | | | Facility | | | Deep Sea Trym | | | | | | | | | | |
| Well | | | 31/5-3-24 AY1H | | | | Field | | | Troil West Gas Province | | | | | | | | | | |
| General | | | | | | | | | | | | | Drill String | | | | | | | |
| Max Allw.SPP | | | 300.00 bar | | | | Type | | | Length | | OD | | ID | | T1 | | Weight | | |
| Surface Equipment | | | Type 4 | | | | Sub - X/O | | | m | | in | | in | | lb/ft | | lb/ft | | |
| Flowrate | | | 4010 l/min | | | | DP - W56 / 5-135 | | | 1945.20 | | 5 1/2 | | 4.78 | | 7 1/4 / 3 1/2 | | 21.90 | | |
| Bit Depth | | | 1982.00 m | | | | HWDP - 5 1/2" FH / | | | 112.38 | | 5 1/2 | | | | | | | | |
| Bit Nozzles in/32 | | | 2x11/7x12 | | | | TFA | | | 0.9587 in ² | | 1.21 | | 7/8 | | | | 3 1/2 | | |
| RWD Nozzles | | | 1" 8 (in/32) | | | | TFA | | | 0.0491 in ² | | 12.84 | | | | | | 20.23 | | |
| RCP | | | 22.00 m/hr RPM | | | | 140 RPM | | | 8.99 | | 7/34 | | 3/16 | | | | 7 1/3 1/2 | | |
| Drilling Fluid | | | | | | | | | | | | | Sub - X/O | | | | | | | |
| Mud System | | | Water Based | | | | Sub - X/O | | | 27.79 | | 5 1/2 | | 1 1/2 | | | | | | |
| Mud Weight | | | 1.250 sg | | | | Slab - string | | | 2.32 | | 8/16 | | 2 1/16 | | | | 156.71 | | |
| Pl V / VP | | | 14.00 cP / 16.65 Pa | | | | Sub - X/O | | | 8.99 | | 9/16 | | 3/8 | | | | 144.16 | | |
| Gel Strength, 10s/10min | | | 5.20 / 7.20 Pa | | | | HWDP - 6 5/8 FH / HW ... | | | 9.30 | | 5/8 | | 4 | | | | 83.32 | | |
| Rheological Model | | | Herschel-Bulkley | | | | Sub - X/O | | | 0.98 | | 7/16 | | 2 1/16 | | | | 146.16 | | |
| Fann 35 Speed | | | K: 1.452(Pa.s ⁿ) n: 0.434 [-] VP: 2.660(Pa) | | | | Bit - Boat | | | 0.77 | | 7/16 | | 2 1/16 | | | | 149.73 | | |
| Fann 35 Reading | | | 600 / 300 / 200 / 100 / 6 / 3 | | | | HW Sub - string | | | 5.34 | | 12 1/2 | | | | | | 158.40 | | |
| | | | 63 / 49 / 39 / 33 / 13 / 1.1 | | | | Sub - X/O | | | 2.30 | | 7/16 | | 2 1/16 | | | | 156.80 | | |
| Casing / Open Hole | | | | | | | | | | | | | Sub - X/O | | | | | | | |
| Type | | | OD | | ID | | Bottom MD | | Sub - X/O | | | 6 5/8 FH / HW ... | | | | | | | | |
| Riser/Booster | | | | | | | | | Sub - X/O | | | 27.84 | | 5/8 | | 4 | | 144.16 | | |
| Casing | | | 13 3/8 | | 12 1/4 | | 1419.00 | | MWD - Nutron/INTEQ | | | 2.65 | | 8/14 | | | | 157.66 | | |
| Openhole | | | 13 1/2 | | 11 1/2 | | 1982.00 | | MWD - Density/INTEQ | | | 2.54 | | 1/4 | | | | 240.86 | | |
| Volumes m ³ | | | | | | | | | | | | | Sub - X/O | | | | | | | |
| Annulus Volume | | | 168.31 Hole Volume | | | | Sub - other | | | 2.73 | | 9/12 | | | | | | 155.62 | | |
| String Displacement | | | 12.17 String Volume | | | | 21.24 | | | MWD - BCPM Std 50mm/... | | | 3.55 | | 1 1/2 | | 1/8 | | 214.85 | |
| | | | | | | | | | | MWD - ONTRAK/INTEQ | | | 7.01 | | 9/12 | | 1/8 | | 322.27 | |
| | | | | | | | | | | MWD - Corus/INTEQ | | | 2.22 | | 9/16 | | | | 322.27 | |
| | | | | | | | | | | Flex sub w/ Stab | | | 3.63 | | 7/16 | | | | 214.85 | |
| | | | | | | | | | | ATK - ASS/INTEQ | | | 2.52 | | 9/12 | | | | 160.04 | |
| | | | | | | | | | | Bit - HCN60/INTEQ | | | 0.37 | | 12 1/4 | | | | 150.00 | |
| Flow Split Results | | | | | | | | | | | | | Sub - X/O | | | | | | | |
| Device | | | Flow Rate | | Bypass | | Ratio | | ΔP | | TFA | | Jet Velocity | | HSI | | Flow Rate Limits Below Split | | | |
| | | | l/min | | % | | % | | bar | | in ² | | m/s | | kW/m ² | | Required | | Critical | |
| Total Flow Rate | | | 4010 | | | | | | | | | | | | | | | | | |
| Bit - under reamer | | | 3755 | | 255 | | 6.3 | | 107.79 | | 0.0491 | | 134.0 | | 2803.80 | | 3314 | | 6942 | |
| Pilot Bit | | | 3755 | | | | | | 61.52 | | 0.9587 | | 101.2 | | 5063.93 | | | | | |
| Total Flow Rate | | | 3710 | | | | | | | | | | | | | | | | | |
| Bit - under reamer | | | 3472 | | 238 | | 6.4 | | 94.38 | | 0.0491 | | 125.3 | | 2297.02 | | 3314 | | 6942 | |
| Pilot Bit | | | 3472 | | | | | | 52.58 | | 0.9587 | | 93.6 | | 4001.02 | | | | 4170 | |
| Total Flow Rate | | | 3410 | | | | | | | | | | | | | | | | | |
| Bit - under reamer | | | 3188 | | 222 | | 6.5 | | 82.21 | | 0.0491 | | 117.0 | | 1867.57 | | 3314 | | 6942 | |
| Pilot Bit | | | 3188 | | | | | | 44.32 | | 0.9587 | | 85.9 | | 3096.93 | | | | | |
| Total Flow Rate | | | 3110 | | | | | | | | | | | | | | | | | |
| Bit - under reamer | | | 2903 | | 207 | | 6.7 | | 71.28 | | 0.0491 | | 108.9 | | 1507.74 | | 3314 | | 6942 | |
| Pilot Bit | | | 2903 | | | | | | 36.76 | | 0.9587 | | 78.2 | | 2339.07 | | | | | |
| Total Flow Rate | | | 2810 | | | | | | | | | | | | | | | | | |
| Bit - under reamer | | | 2619 | | 191 | | 6.8 | | 60.95 | | 0.0491 | | 100.7 | | 1191.99 | | 3314 | | 6942 | |
| Pilot Bit | | | 2619 | | | | | | 29.91 | | 0.9587 | | 70.6 | | 1716.76 | | | | | |
| Total Flow Rate | | | 2510 | | | | | | | | | | | | | | | | | |
| Bit - under reamer | | | 2334 | | 176 | | 7.7 | | 51.28 | | 0.0491 | | 92.4 | | 919.97 | | 3314 | | 6942 | |
| Pilot Bit | | | 2334 | | | | | | 23.77 | | 0.9587 | | 62.6 | | 1216.31 | | | | | |

Going farther faster – Drilling Optimization (Barnett Shale example)

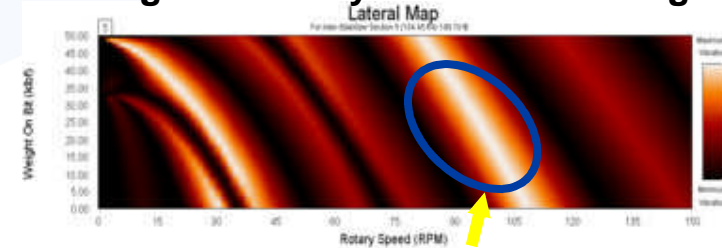
Drilling Challenges



- Premature Damage to PDC Bits
- Low ROP, More Bits Required
- High Cost Per Foot
- High Torque and Drag
- Excessive Slide Drilling (Oriented) in Lateral Interval
- Damaging Drill String Vibrations
- Low Reliability/Performance of Downhole Tools

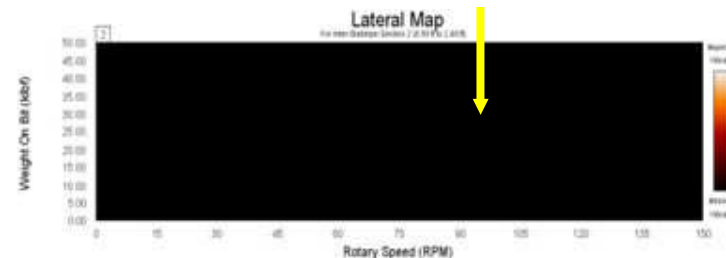


Buckling Load Analysis/ BHA Re-design



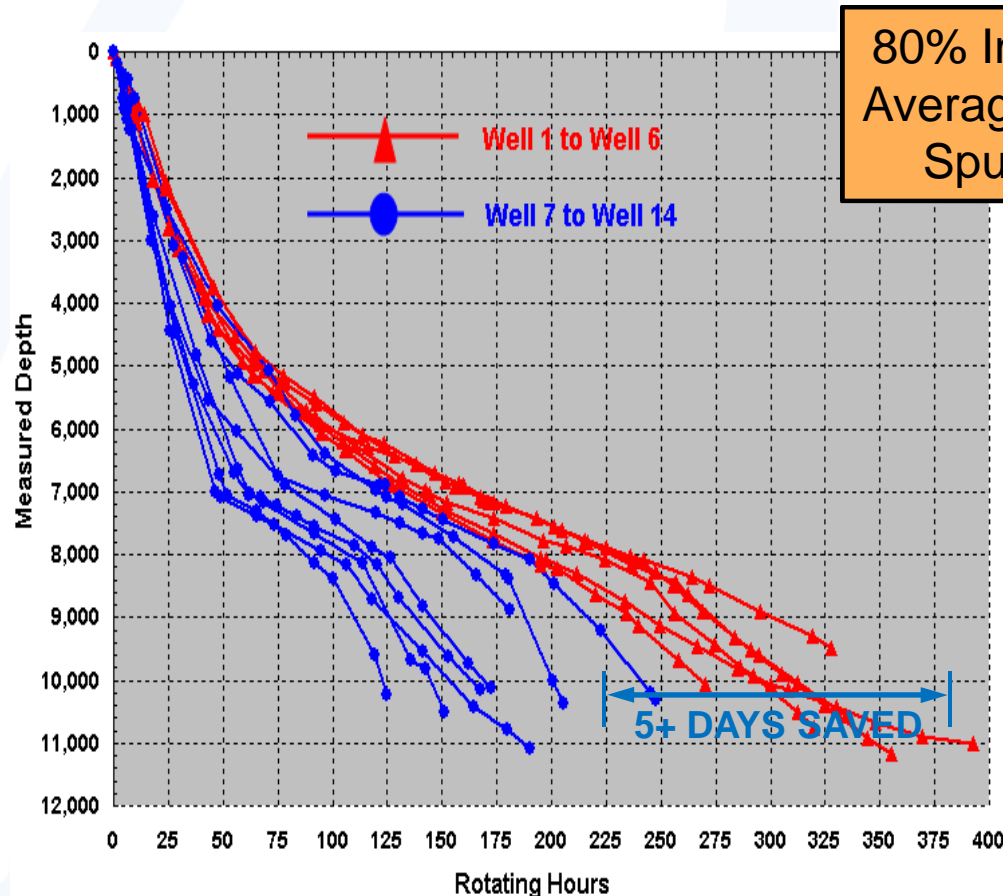
Away from Bit - High Vibration

Closer to Bit - Minimum Vibration



Critical Speed Analysis – Optimize Drilling Parameters

Drilling Optimization (Barnett Shale Example)



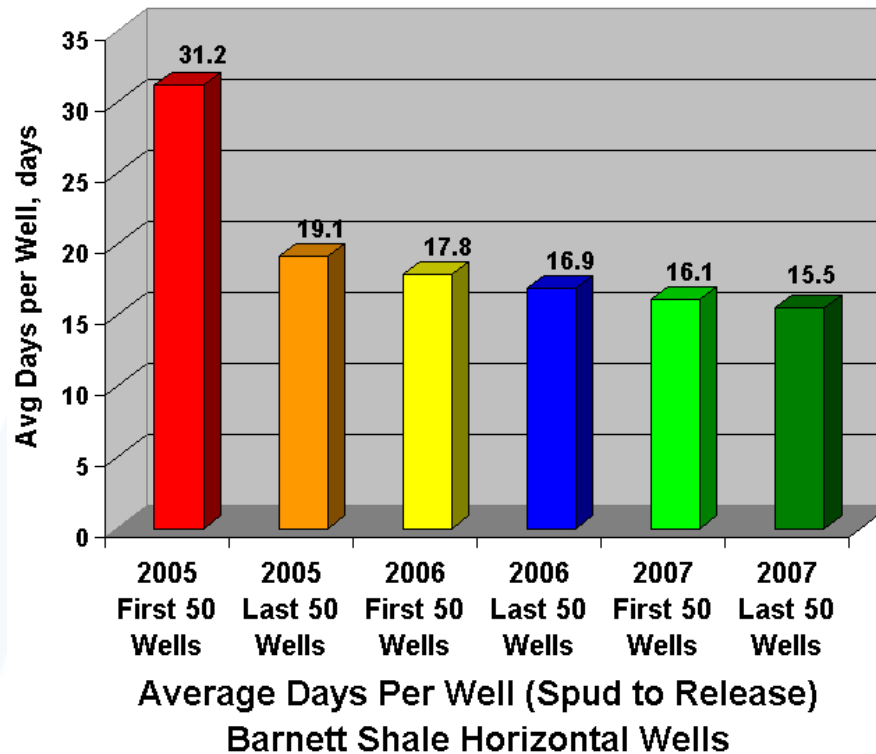
80% Increase in
Average ROP for
Spud to TD

Optimization

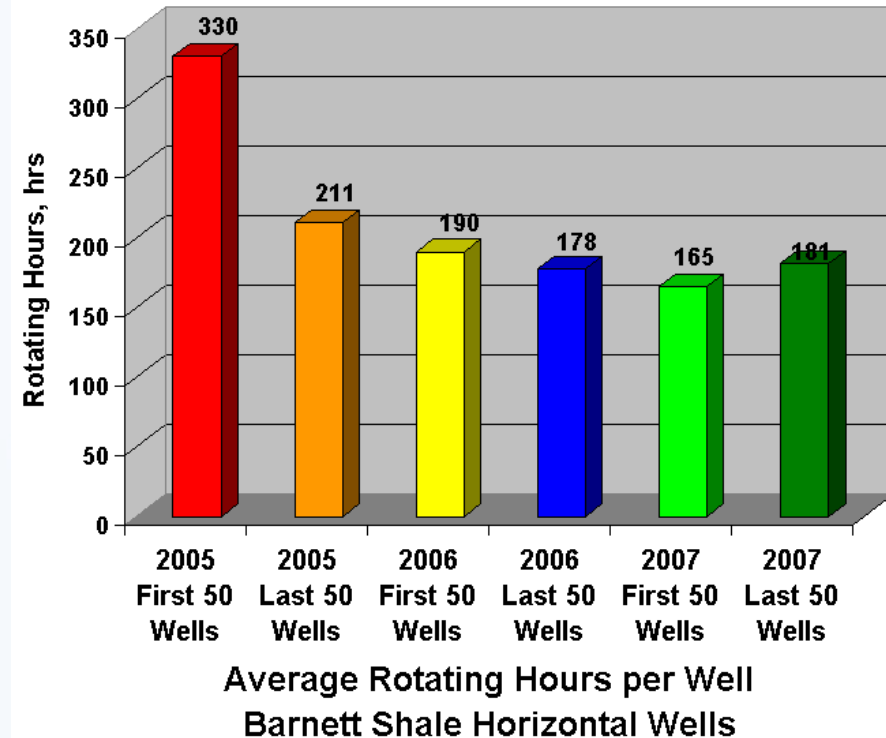
- Modified PDC Bits
- Model Re-design BHA
 - torque, drag, hydraulics
- Optimized Parameters - WOB, Rotation
- Critical Speed Analysis to reduce vibration
- Result - increase ROP

6 Wells Drilled Prior to Optimization @ 32 ft/hr
8 Wells Drilled After Optimization @ 57 ft/hr

Barnett Shale – Drilling Performance



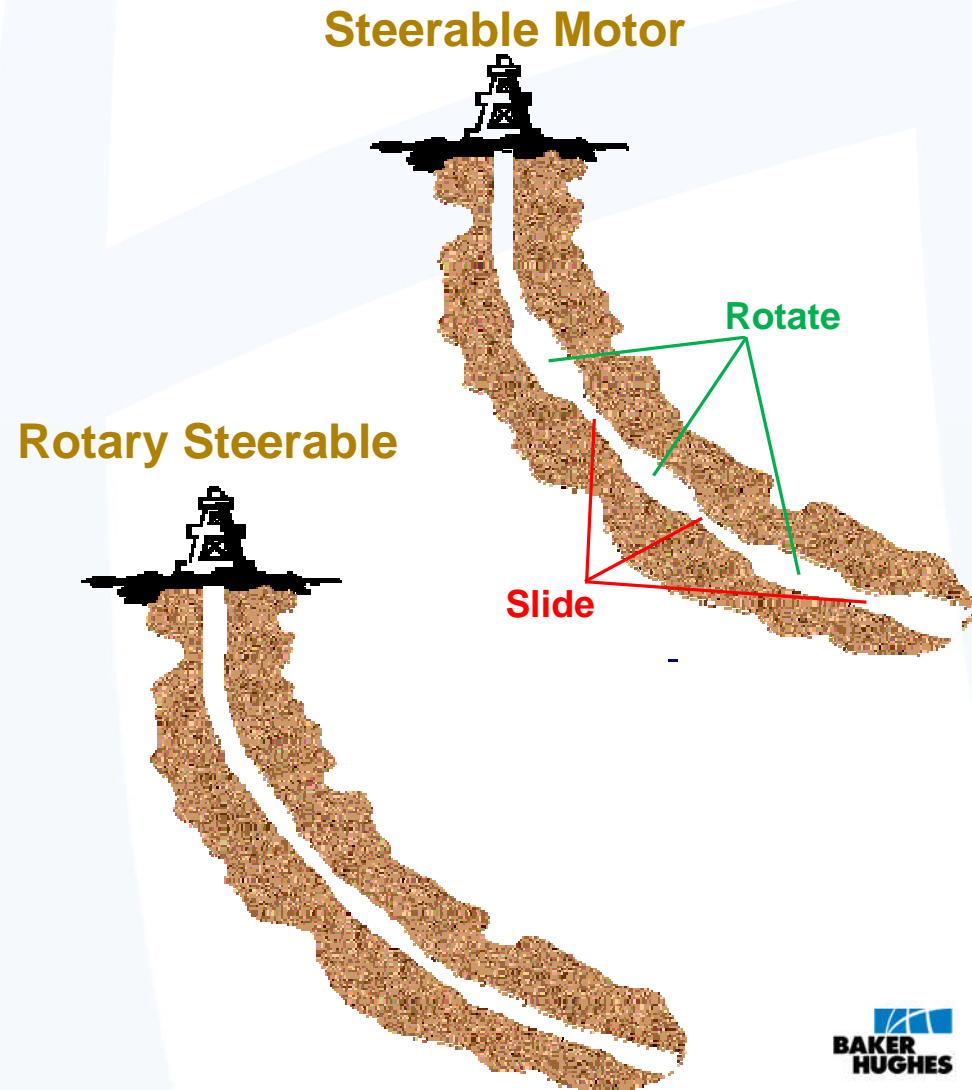
Average days per well
reduced from
31.2 to 15.5 days



Average rotating hours per well
reduced from
330 to 181 hours

Decrease risk and reduce time on well utilizing Rotary Steerable Tools – Shale Gas Laterals

- Decrease risk
 - Improved borehole quality allows for casing running operations to be completed with less risk for extended reach laterals
- Reduce time on well
 - Eliminating orient and slide time associated with steerable motor drilling improves overall effective penetration rate



Eagle Ford - Webb County – AutoTrak G3 / OnTrak

Well Details

- Well Details
- Location: Webb County
- Shale Play: Eagle Ford
- Hole Size: 8 3/4" Curve and Lateral

Challenges

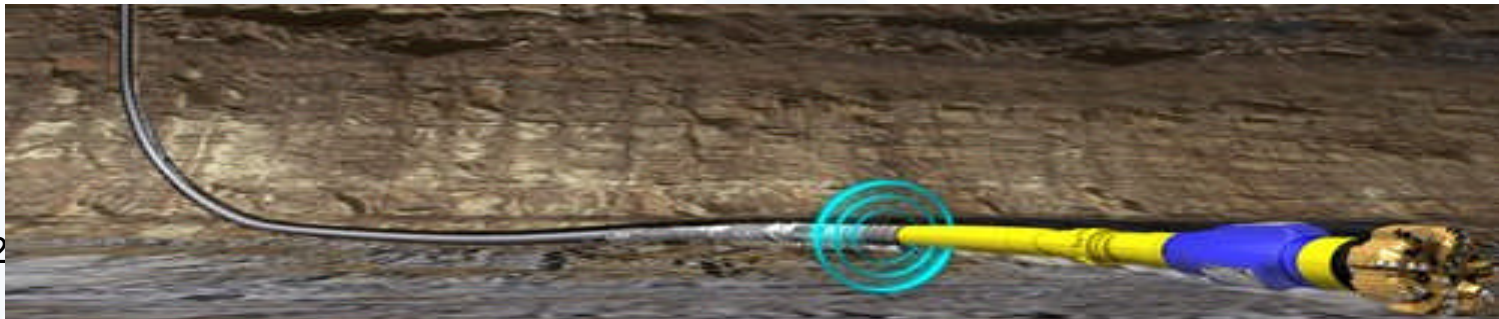
- Low ROP's
- Several Bits Required
- Inconsistent BUR's in Curve
- Trips to change BHA's
- Reduced Drilling Efficiency
- High Cost per foot
- Difficulties staying in Zone

Solution

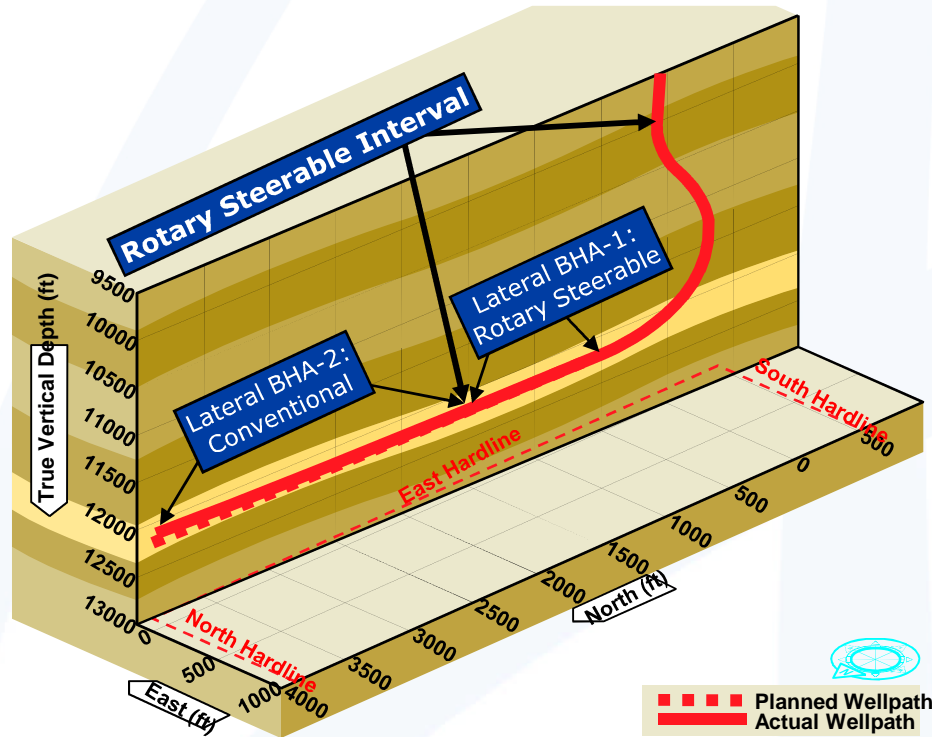
- 8 3/4" HCC Bit (DP505X PDC Bit)
- 6 3/4" AutoTrak G3 RSS
- 6 3/4" OnTrak LWD

Project Results

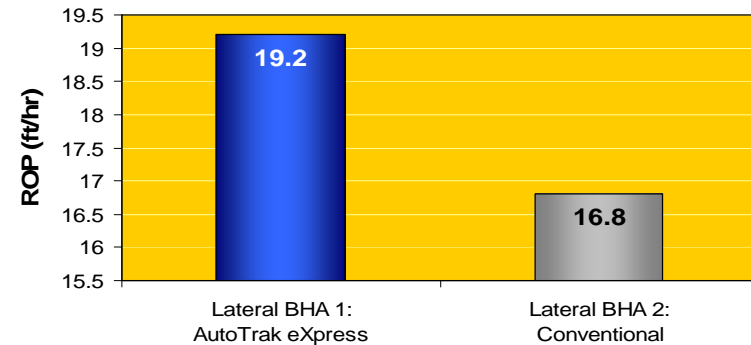
- Drill Curve from 23 deg inclination and land the curve
- Continue Drilling Entire Lateral of 3,748 ft to TD
- Total Footage: 5,113 ft
- Rotating Hrs : 97.75 hrs
- Average ROP: 52.3'/hr
- Eliminated Reaming
- Smoothly Ran Liner to Bottom
- Consistent BUR's
- Stayed in Desired Zone



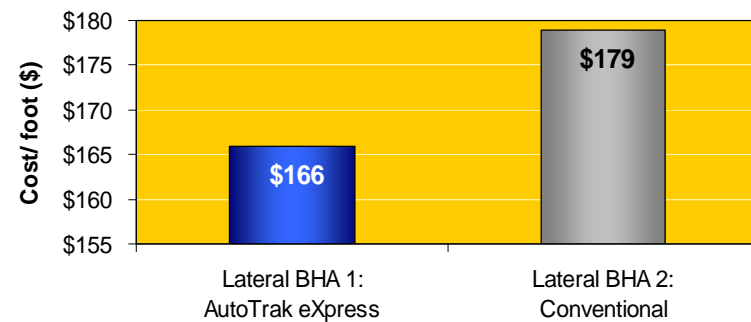
Woodford Shale – Rotary Steerable



Rotary Steerable Improved ROP by 15%



Rotary steerable Reduced Cost/ Foot by 7%

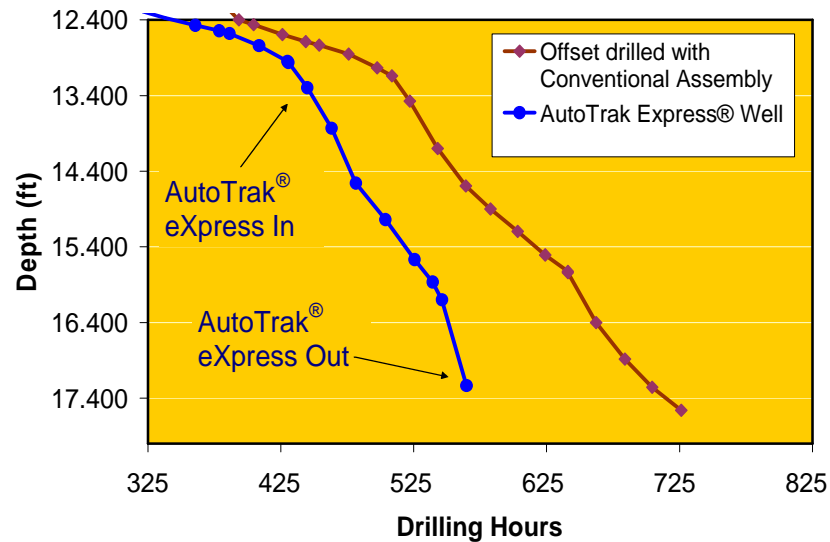


Woodford Shale – Rotary Steerable

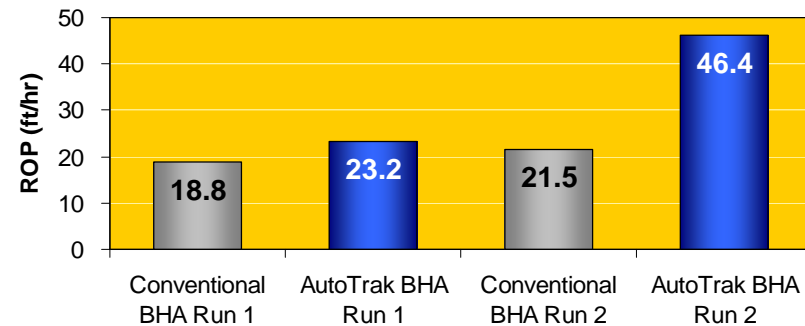
AutoTrak[™]
eXpress

Automated Rotary Steerable Drilling

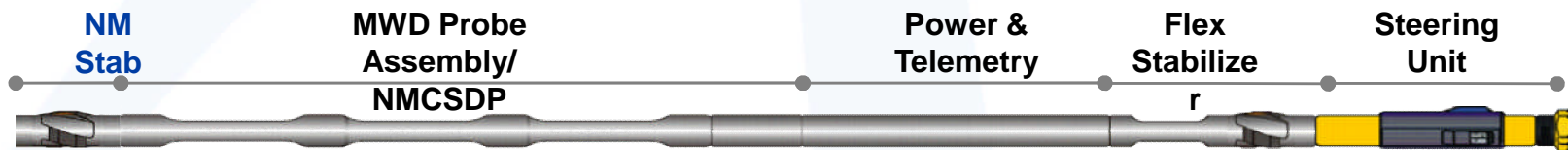
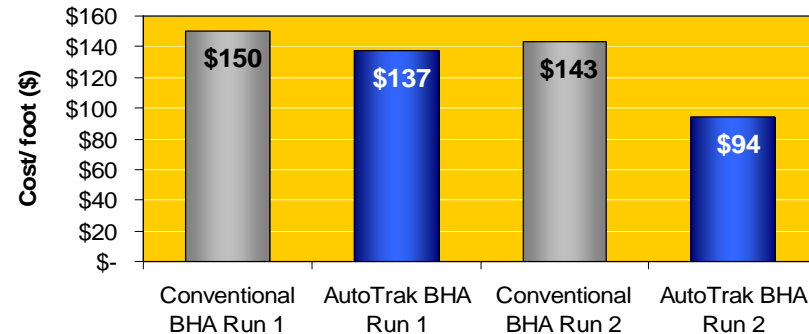
AutoTrak Express[®] Saved 4 Days of Rig Time



Rotary Steerable Improves ROP by 115%



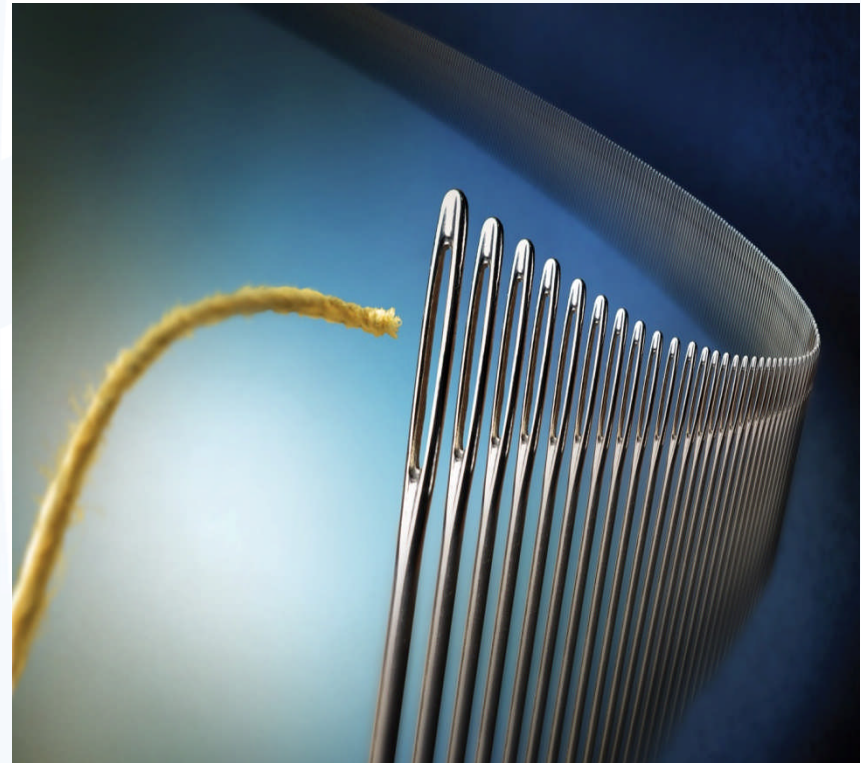
Rotary Steerable Reduces Cost/ft by 34%



**BAKER
HUGHES**

Maximizing production by optimizing wellbore placement –Shale Gas

- Reservoir Navigation
 - Full suite of formation evaluation tools and services to steer to the reservoir “sweet spot”



Reservoir Navigation – Woodford Shale

Project Results

- Well was maintained in target zone
- Reservoir Navigation Services
- Multiple Propagation Resistivity
- Azimuthal Gamma Ray
- Gamma Ray Imaging
- Annular and Bore hole pressure

Fig. 2: Gamma Image of Well A

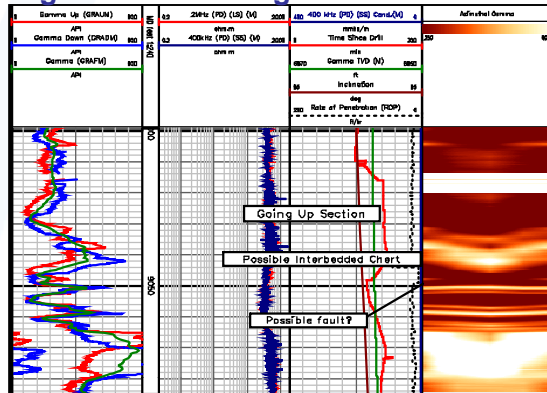


Fig. 4: Gamma Image of Well B

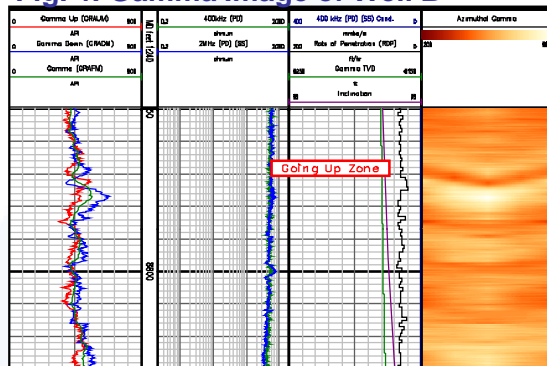


Fig.1: RNS CROSS SECTION – Well A

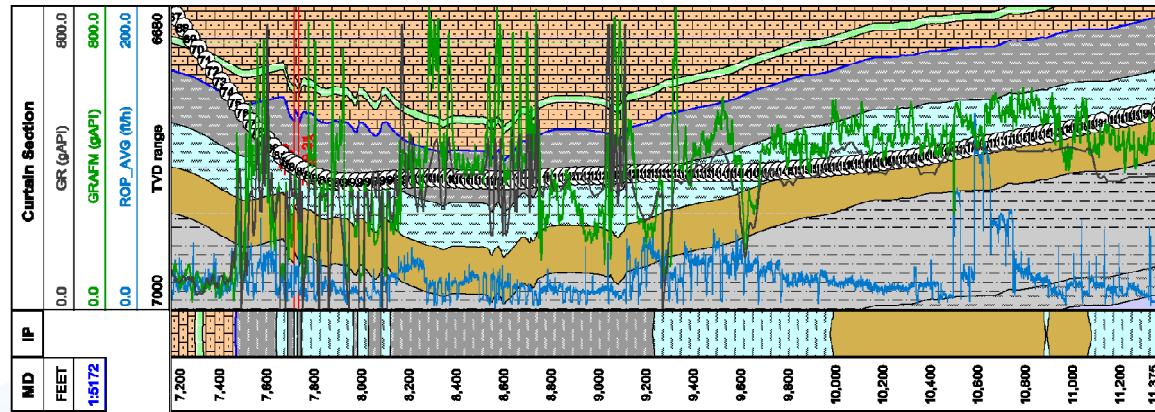
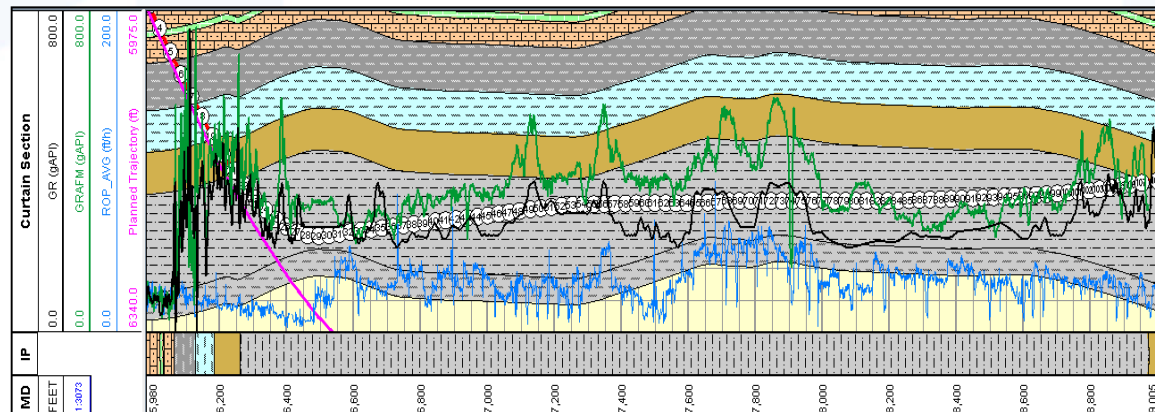
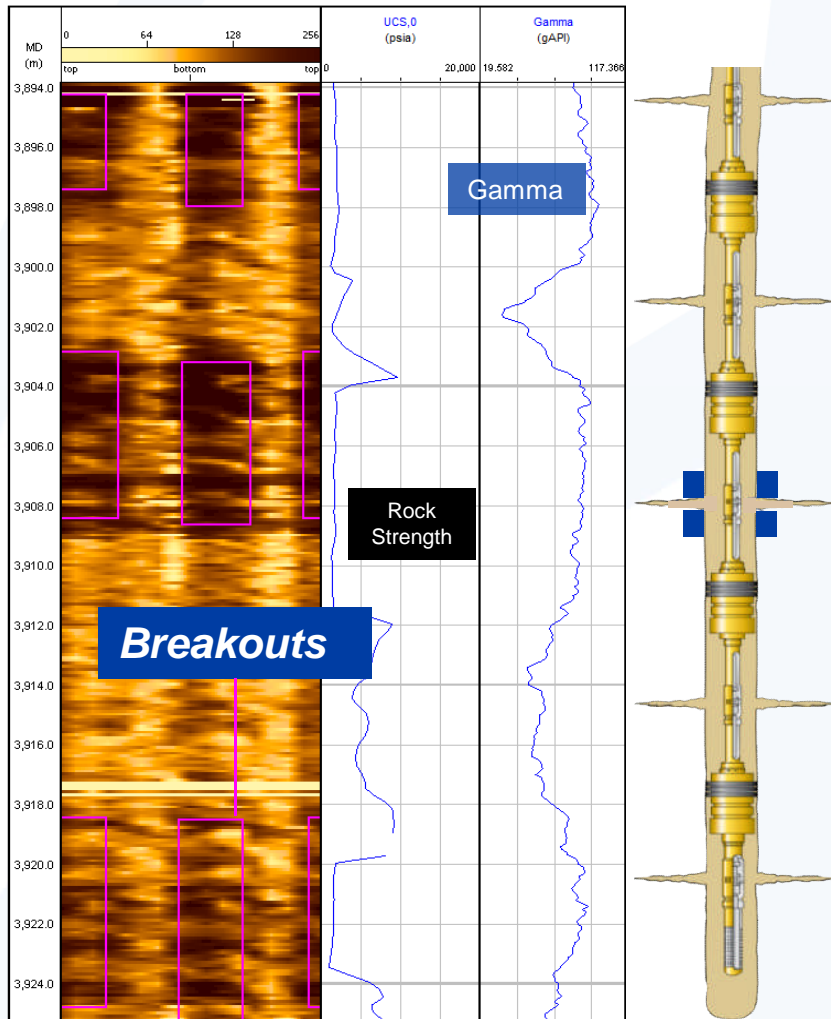


Fig.3: RNS CROSS SECTION – Well B



LWD Image in Shale Gas

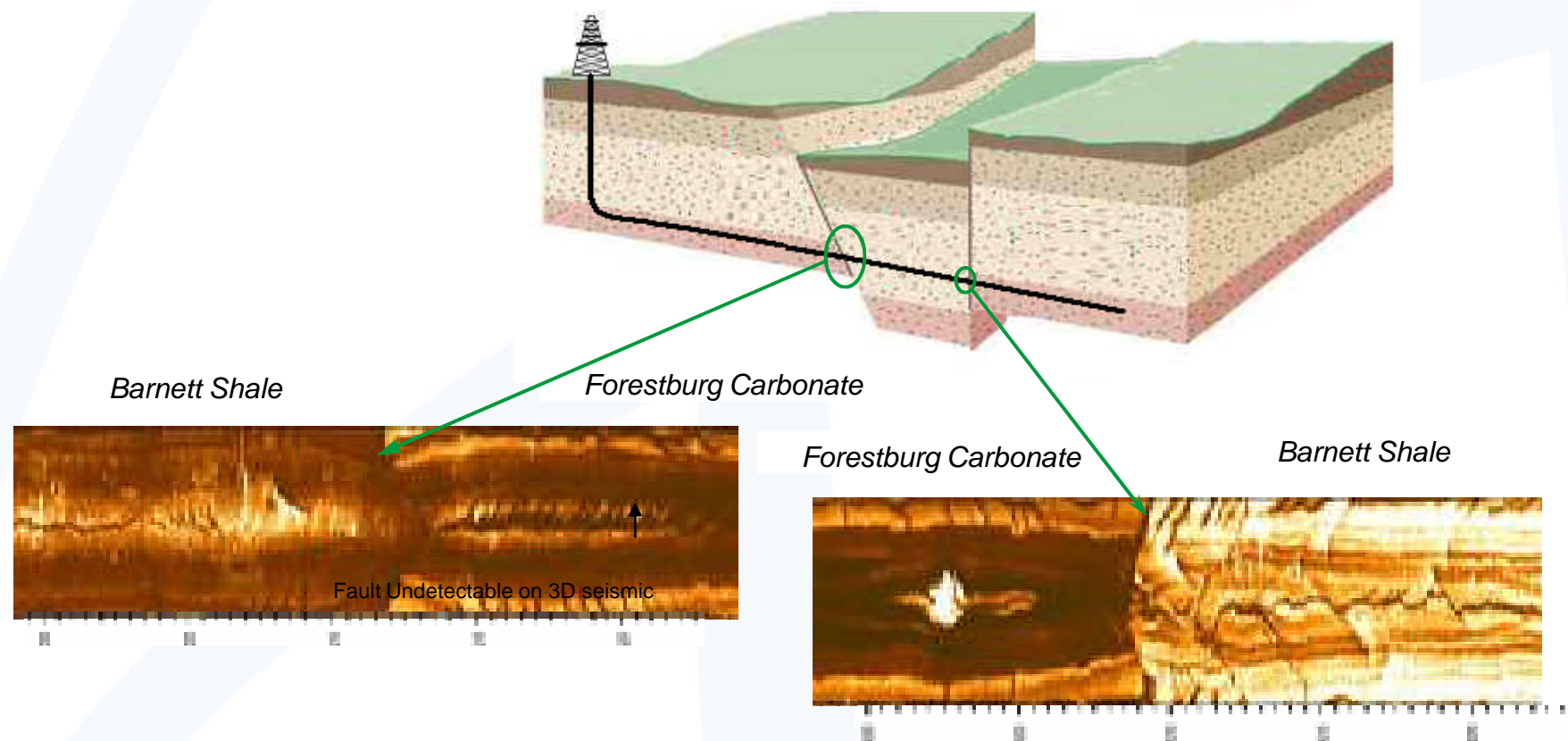


LWD Can be used to identify:

- Fracture
- Lithoface good for fracturing
- Optimization of perforating interval
- Optimization of packer placement
- Fracturing length

Integrated fracturing design

Faults and Fractures in Barnett Shale Horizontal Well





Thank You